AC-Induced Cyclic Deformation in Aluminum Interconnects

R. R. Keller
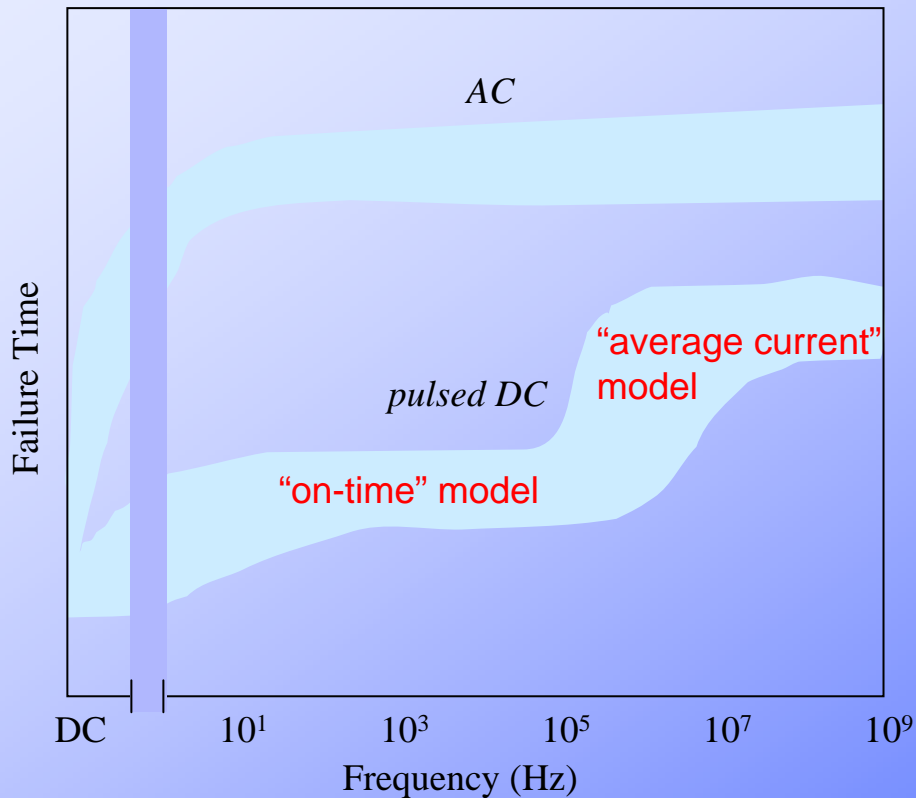N.I.S.T. Materials Reliability Division
Boulder, CO

R. Mönig, C. A. Volkert, E. Arzt, and O. Kraft
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- Strange, Irreversible Damage
- Temperature and Stress
- Fatigue
- Effects of Passivation
- Concluding Remarks

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What is Known about non-DC EM?

Generally, non-DC stressing leads to longer, but nonetheless finite lifetimes.

There is a "healing" effect when the current is reversed.

So, why bother??

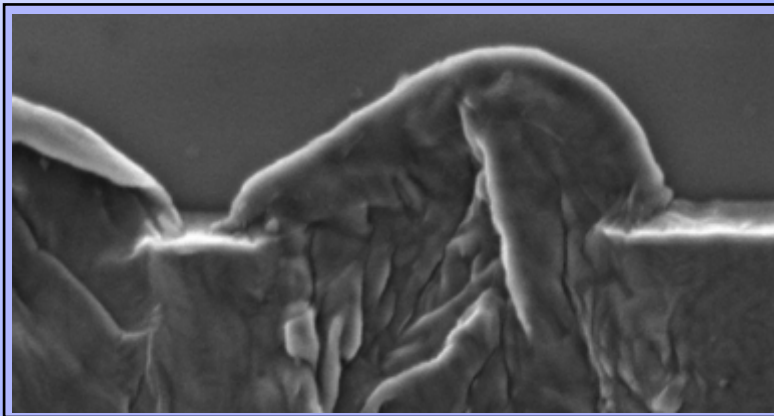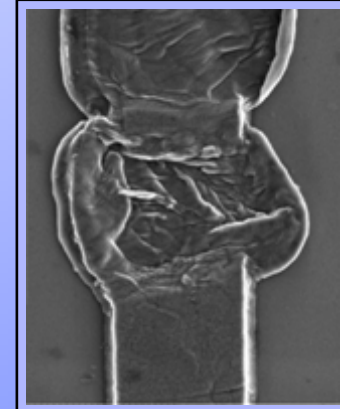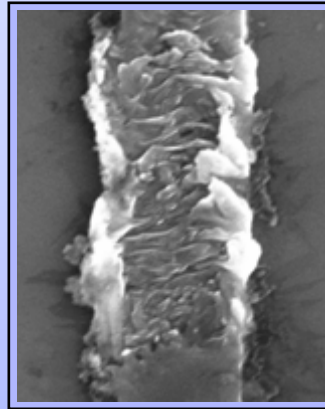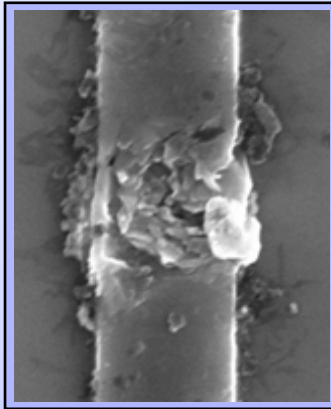VOLKERT, C. A., "Electromigration in Interconnects"
To be published in Encyclopedia of Materials: Science and Technology, Eds. K.H.J. Buschow,
R. Cahn, M. Flemmings, B. Ilschner, E.J. Kramer, S. Mahajan, Elsevier Science Ltd., Oxford, UK

Electromigration
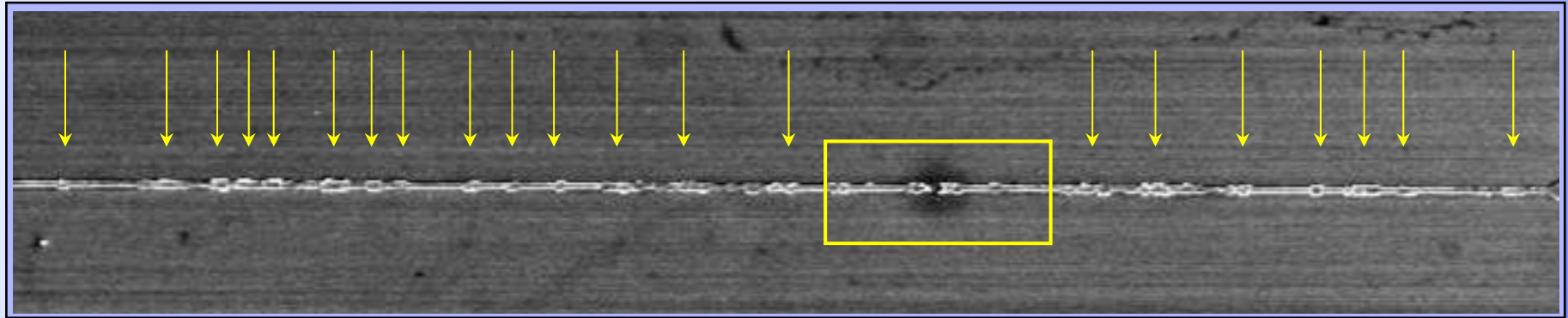# as You've Never Seen It Before?

Unpassivated Al-1Si, "conventional" processing

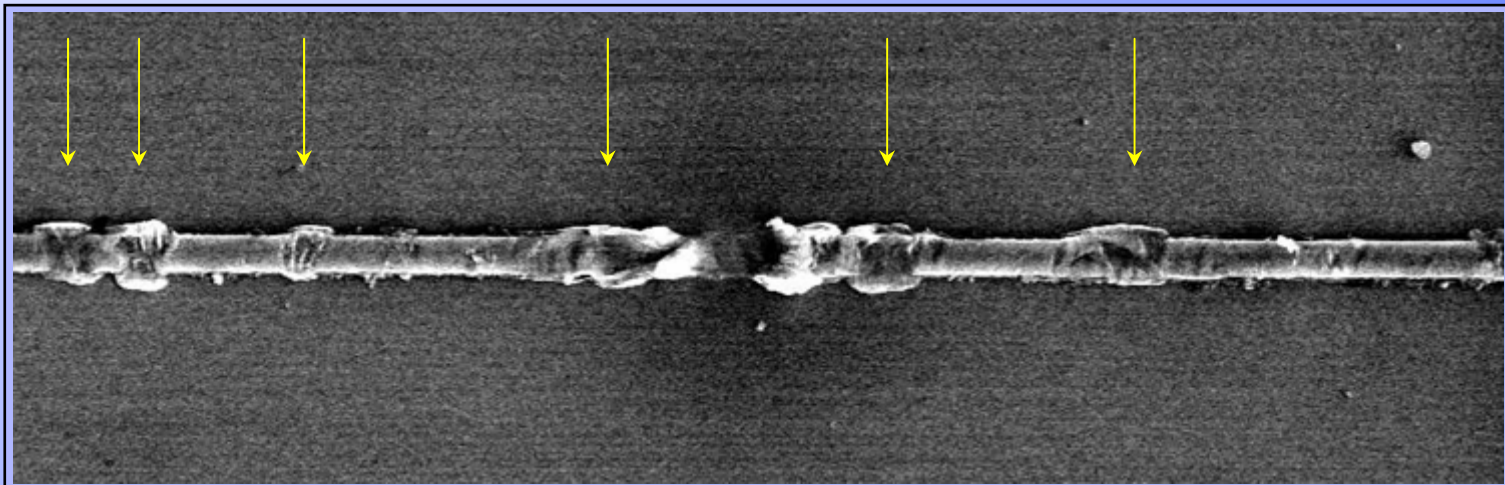Tested at 20° C (nominally), 100 Hz, sinusoidal AC, 0 A DC offset

~10 MA/cm^2 current density
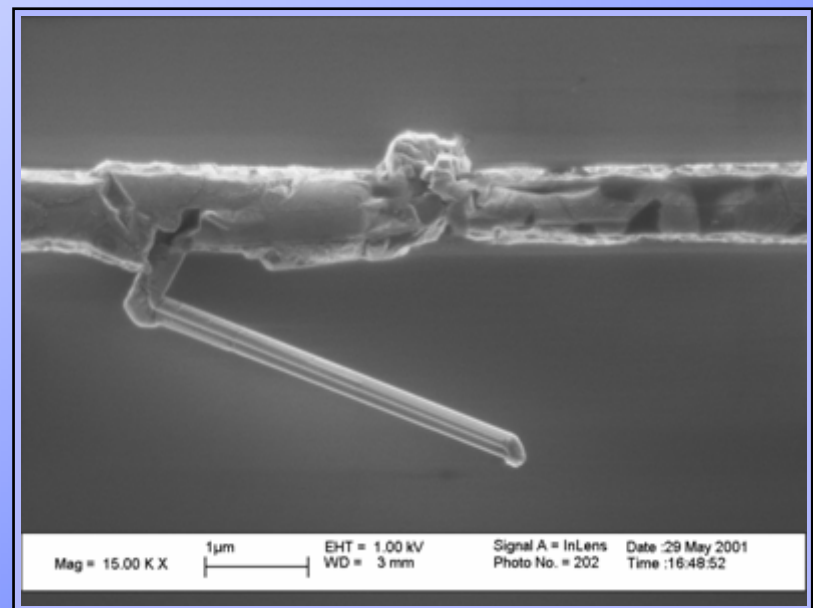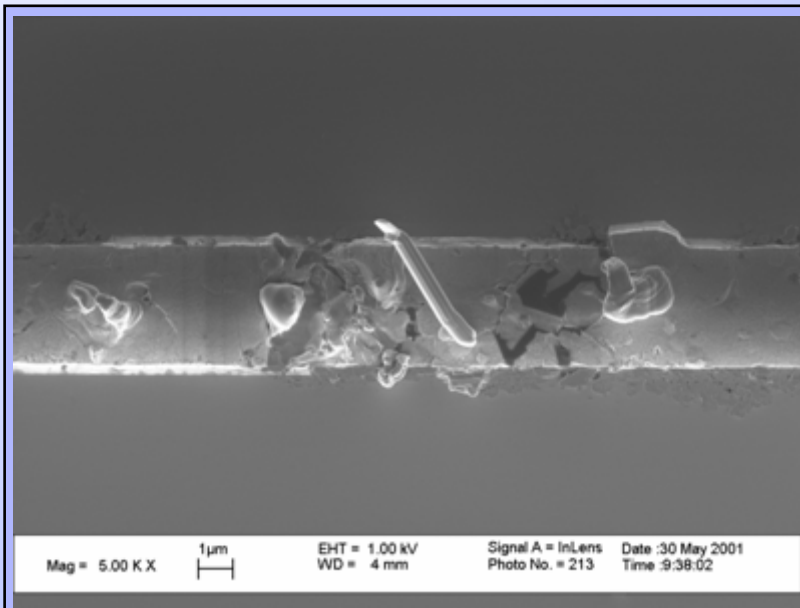
Distribution of Cyclic Damage

100 µm

10 µm

DC Testing at these Current Densities

DC damage looks considerably different from AC damage.

Characteristic Distances

General Distance Estimate
at 100 Hz, t = 0.01 s: $x \approx \sqrt{Dt}$

Diffusion Distances during 1 Cycle at 100 Hz

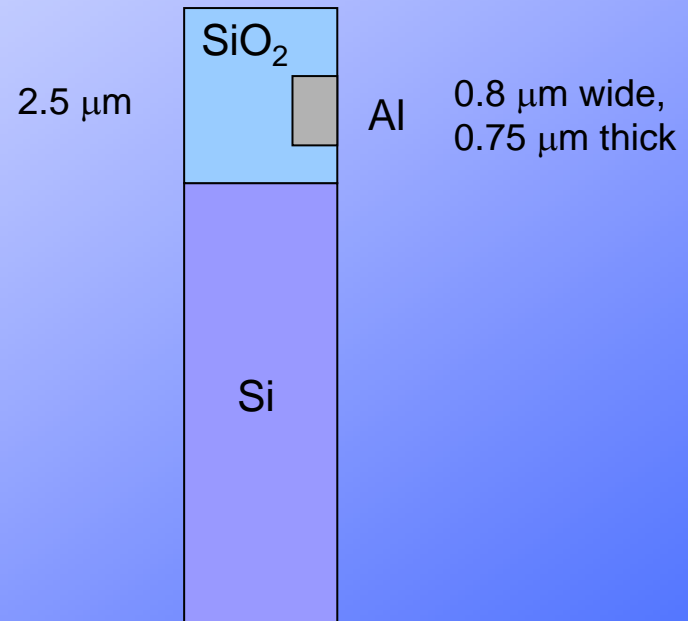|	D (m^2/s)	x
Grain Boundary Diffusion	10^{-15}	3 nm
Lattice Diffusion	10^{-18}	0.1 nm
Thermal Diffusion	**10^{-4}**	**1 mm**

It is questionable whether atomic diffusion plays an important role.
But **temperature** may...

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Temperature Change in Each Cycle

Temperature Rise during 1 Cycle at < 250 Hz

| j (MA/cm^2)	ΔT (°C)
0.1	~ 0
1.0	2
2.0	8
3.0	18
…	…
10	200

SiO$_2$

2.5 μm

Al

0.8 μm wide, 0.75 μm thick

Si

X. Gui, J.W. Haslett, S.K. Dew, and M.J. Brett, "Simulation of Temperature Cycling Effects of Electromigration Behavior Under Pulsed Current Stress," IEEE Trans. Electr. Dev. 45, 380-386 (1998).
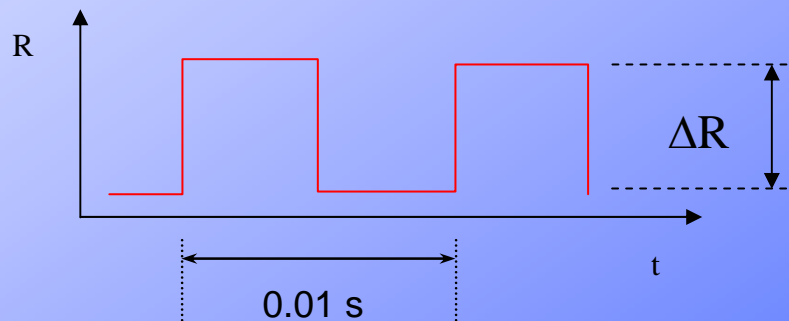
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Temperature Changes due to Joule Heating

Performed calibration of R vs. T:
- low AC current,
- sample in furnace,
- allowed to equilibrate

ρ vs. T

$\rho = 0.0081T + 1.9386$

ρ (μΩ-cm)

T (ºC)
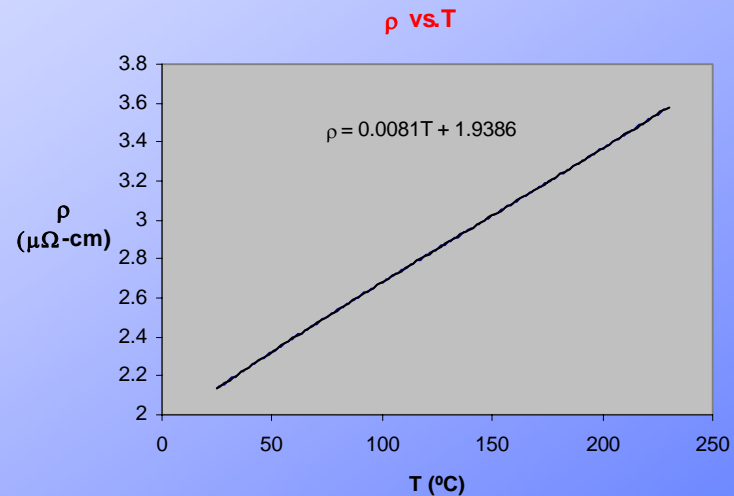
Examined square waveform (same power as sine) using oscilloscope:

R

ΔR

0.01 s

t

$\Delta T \approx 50 - 100°C/cycle$
for 10 MA/cm^2

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Thermomechanical Stresses

$\varepsilon_{\text{thermal}} = \Delta\alpha\,\Delta T$ (between Al and Si)

$$\Delta\alpha = 20 \times 10^{-6} / K \qquad \Delta T \approx 100°C$$

$\varepsilon_{\text{thermal}} \approx$ 0.2% total strain per cycle

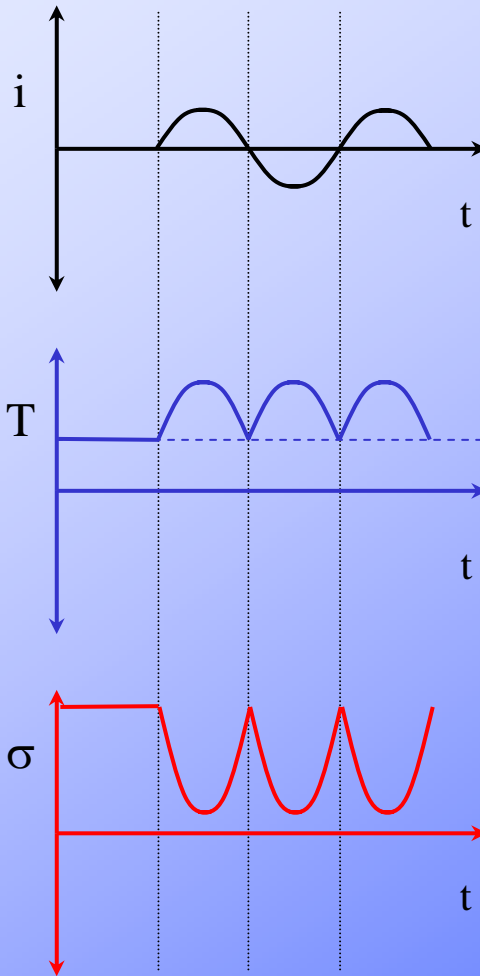$\sigma_{\text{thermal}} \approx$ 140 MPa /cycle,

i.e. comparable to macroscopic yield stress

For comparison, σ_{ys} (thin Al film) $\approx$ 120 MPa

On local scale, flow stress could be exceeded, due to dislocations, grain boundaries, etc. (basis for fatigue)

Temperature/Stress Behavior During AC Cycling
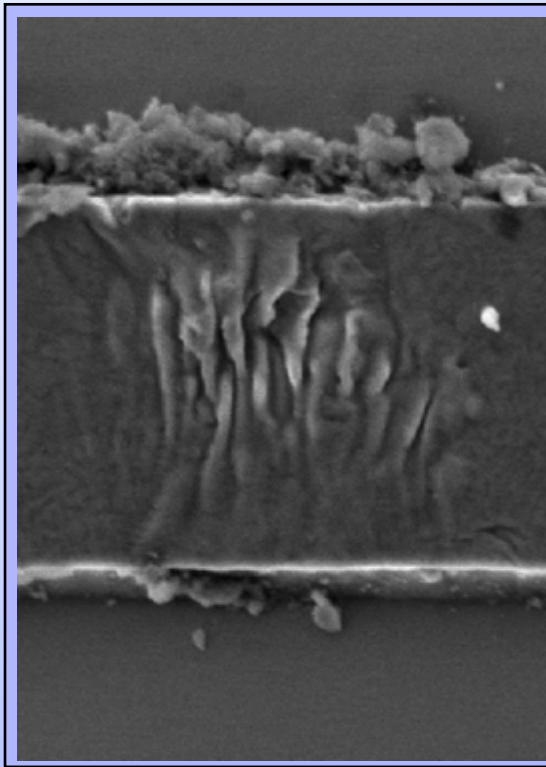
$\Delta T \sim$ power $\sim i^2$

$\sigma \sim \varepsilon \sim \Delta T$

Note: 100 Hz AC $\Longrightarrow$ 200 Hz fatigue

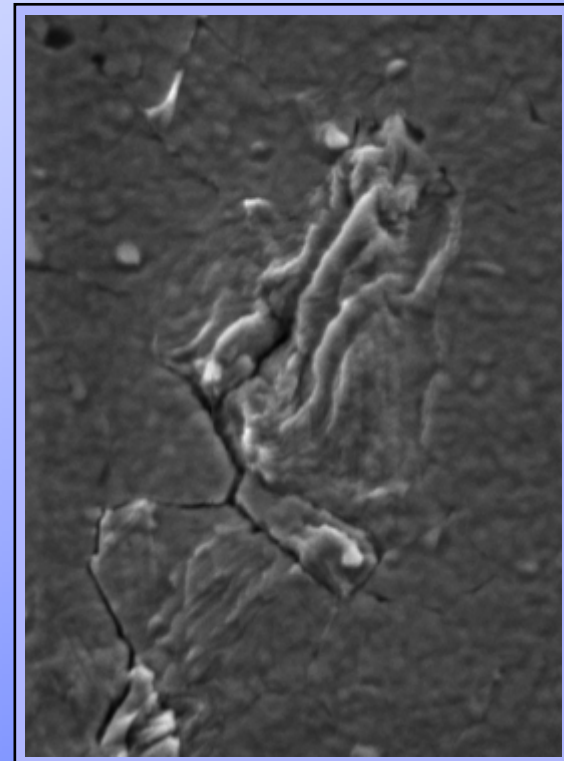Tension-tension depicted here. Could go tension-compression, depending on ΔT, $\sigma_{residual}$.

AC Damage Resembles Fatigue Damage
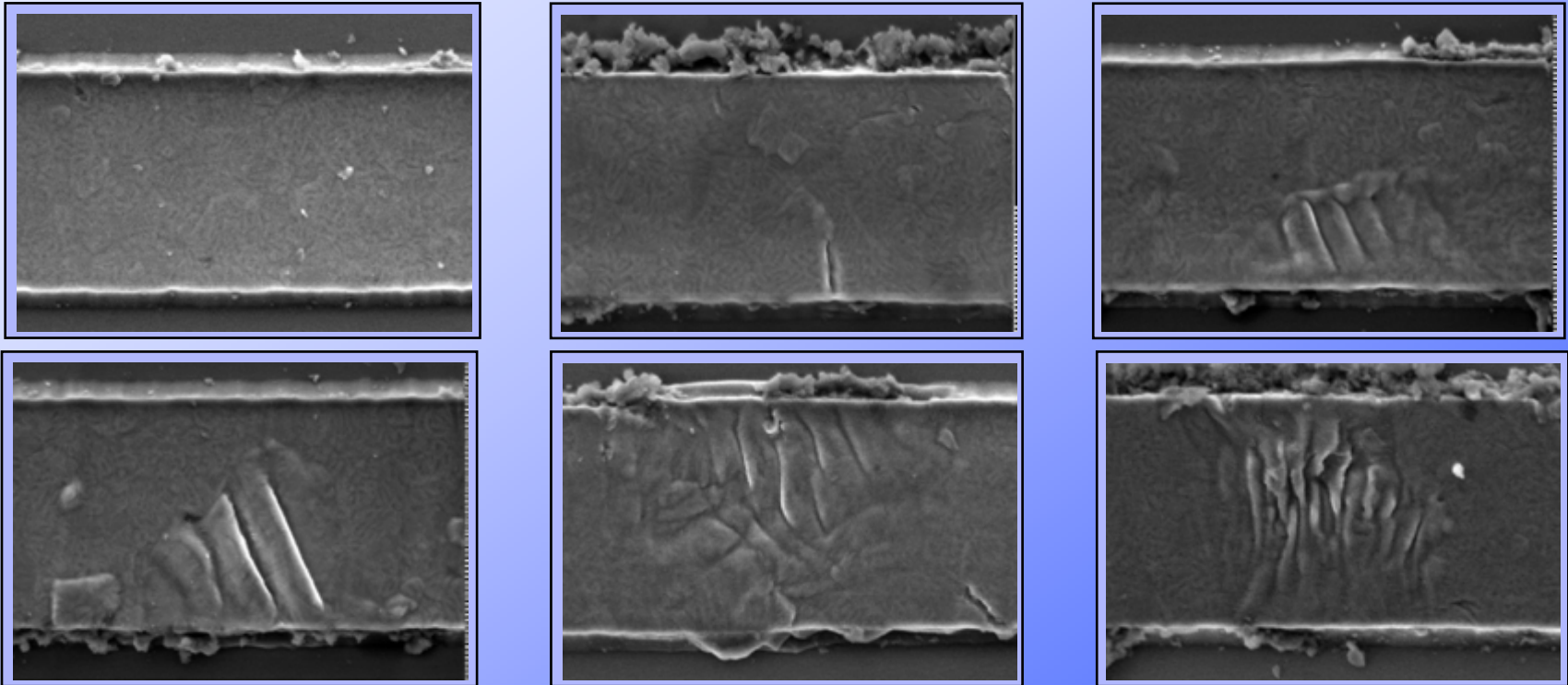

Load

$\overline{}$
1 μm

6×10^6 cycles
$j = 10$ MA/cm^2, $\Delta\varepsilon \approx 0.2\%$
100 Hz AC
Al-1Si

10^6 cycles
$\Delta\varepsilon = 0.8\%$
10 Hz
Pure Al

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Damage *Distribution* <u>at a Given Time</u> During Such a Test

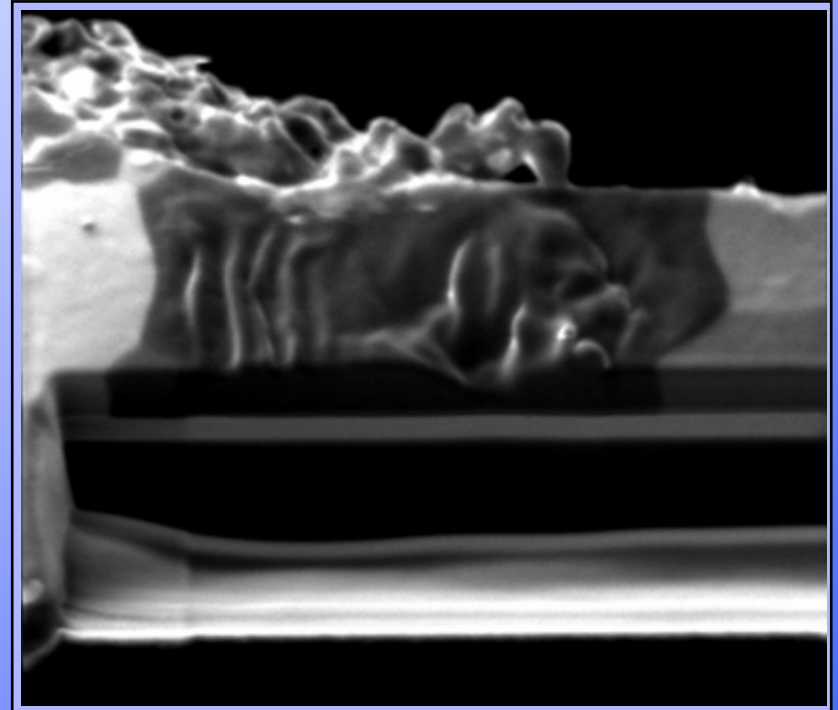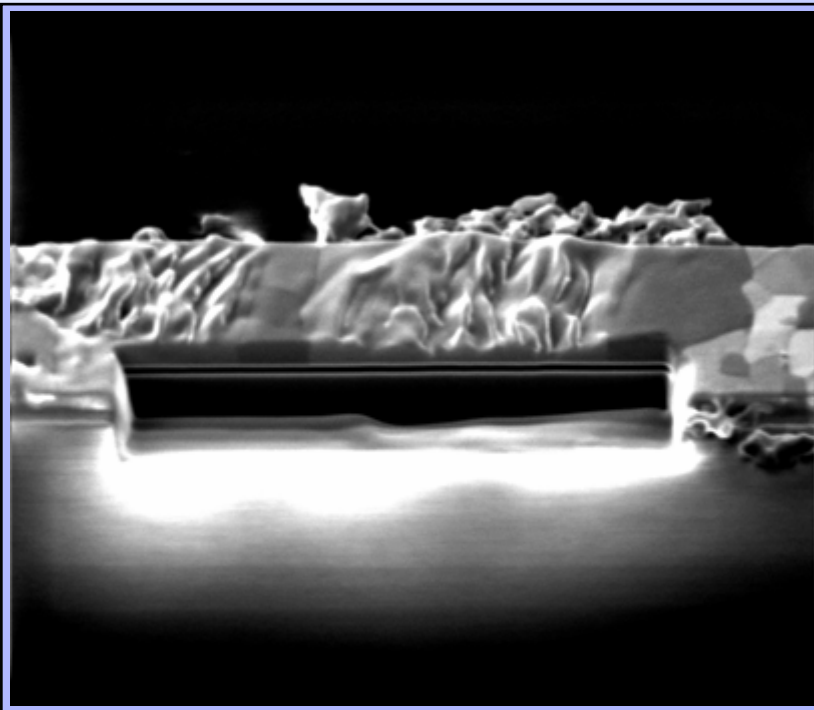Ranges from seemingly untouched to drastically altered areas:

Varying degrees of plasticity suggest progression in "slip order", dependent upon crystallography.
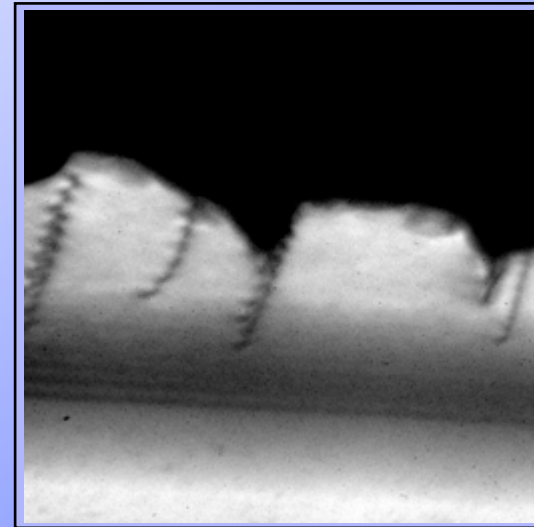
1 μm
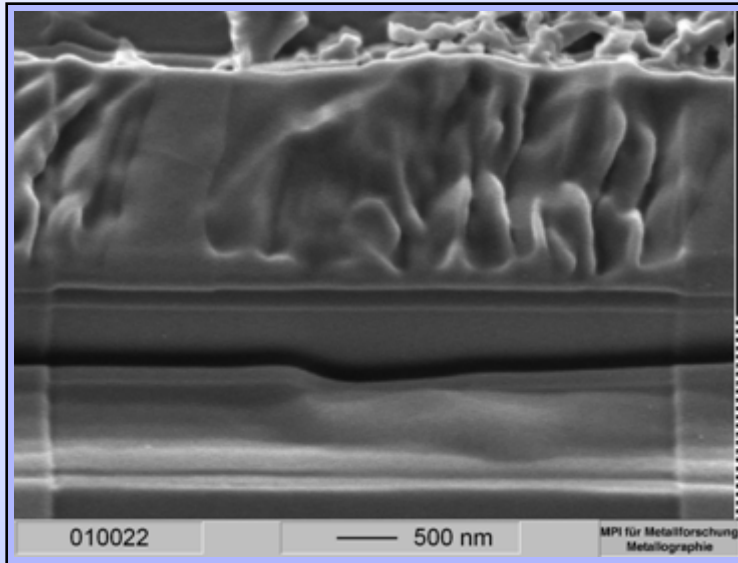
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Cross-Sections

Damage appears confined to individual grains:

EBSD measurements underway...
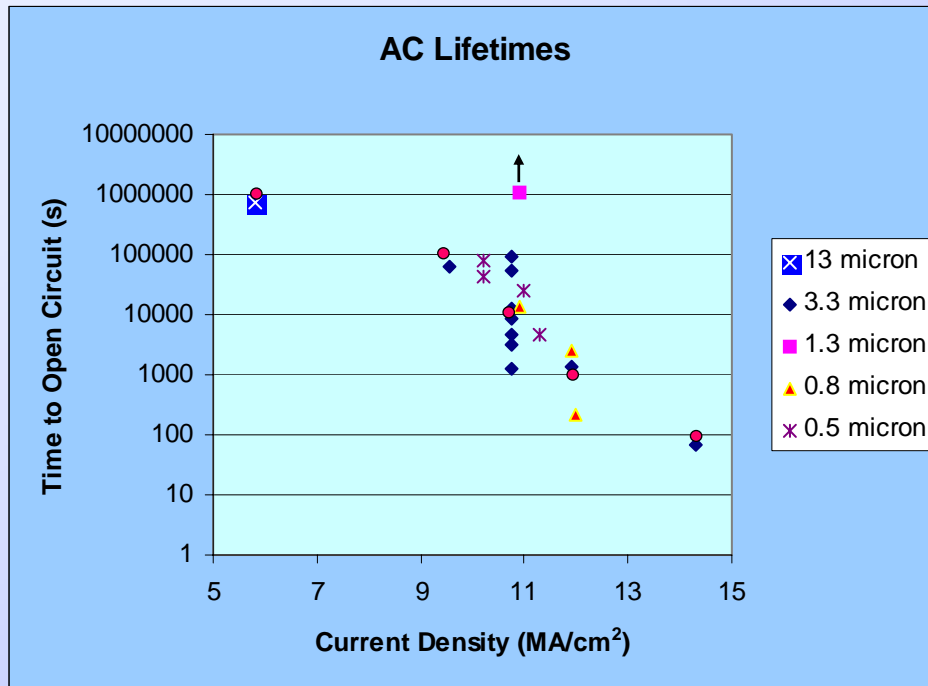
Dislocations?

0.5 μm

Considerable topography, reminiscent of fatigue-induced slip upsets.
NO dislocation structures typical of advanced stages of fatigue in bulk
metals, *i.e.* cells, PSBs, not even tangles.

Effect of confined volume? Looks rather like the Nix picture...
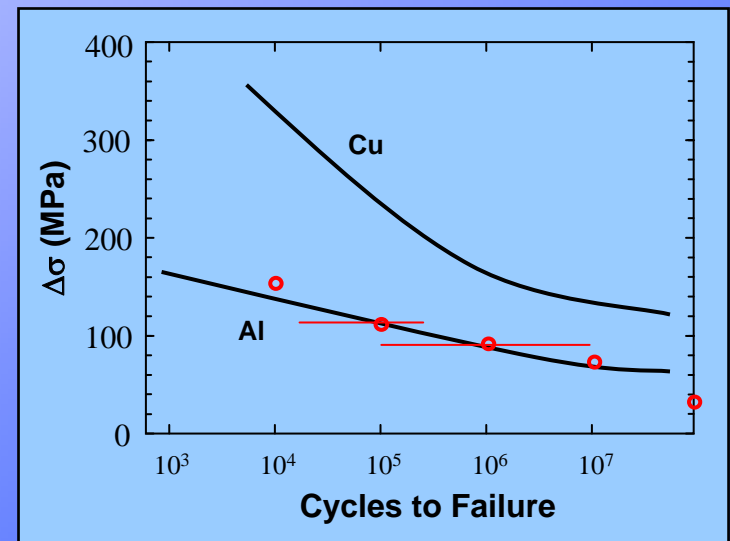
Need more TEM in any case!

Lifetimes

AC Lifetimes

Time to Open Circuit

• Used in S-N Plot

S-N Representation of Fatigue Life

Fatigue Failure

Crack initiation at free surfaces:
- evolution of lower energy dislocation structures
    - tangles, cells, PSBs
- stress concentrations and surface topography
- extrusions and intrusions

During AC stressing:
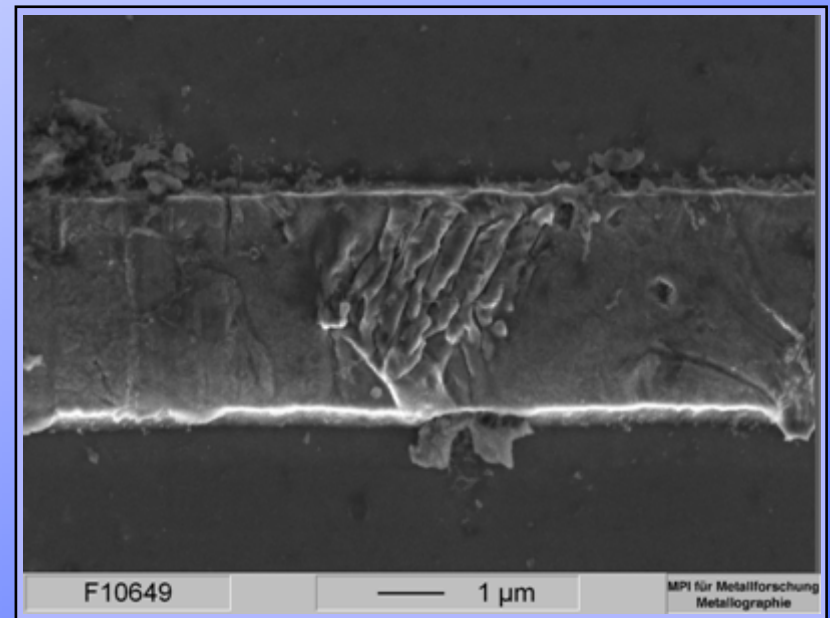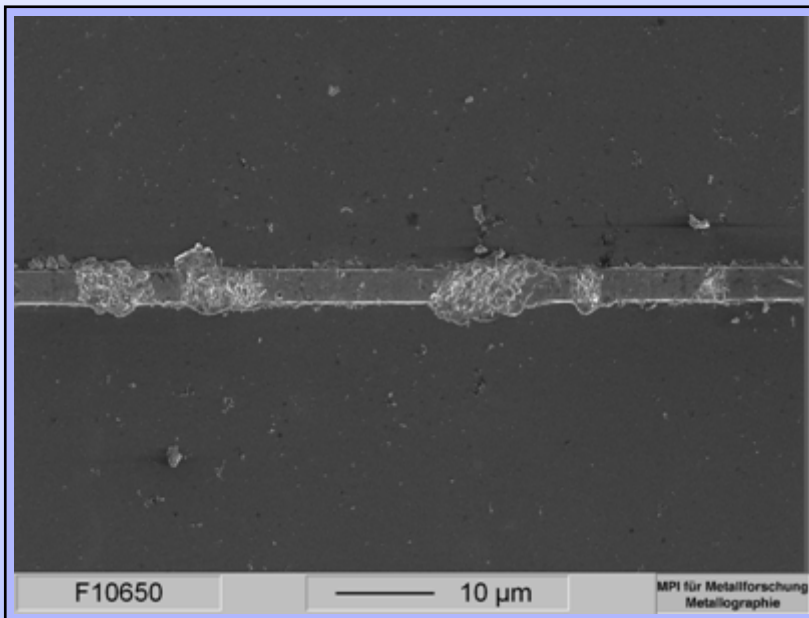- j increases as cross-section decreases

→ may not get cracking

If fatigue analogy is correct:

Hard passivations (*e.g.* oxides, nitrides) may retard damage
Soft overlayers (*e.g.* low-k polymers) perhaps not so effective...

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Effect of Soft Passivation

Coated with 2 μm photoresist (cured)
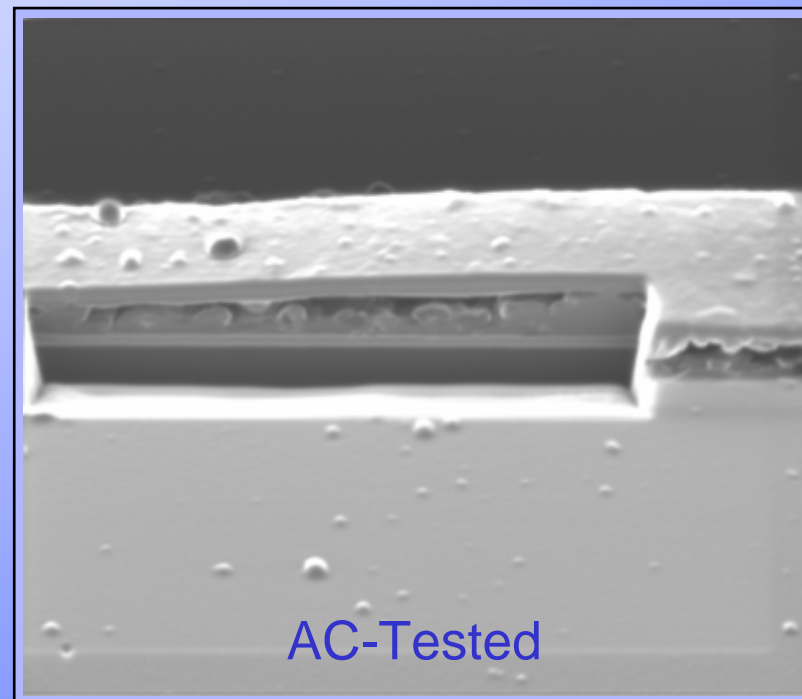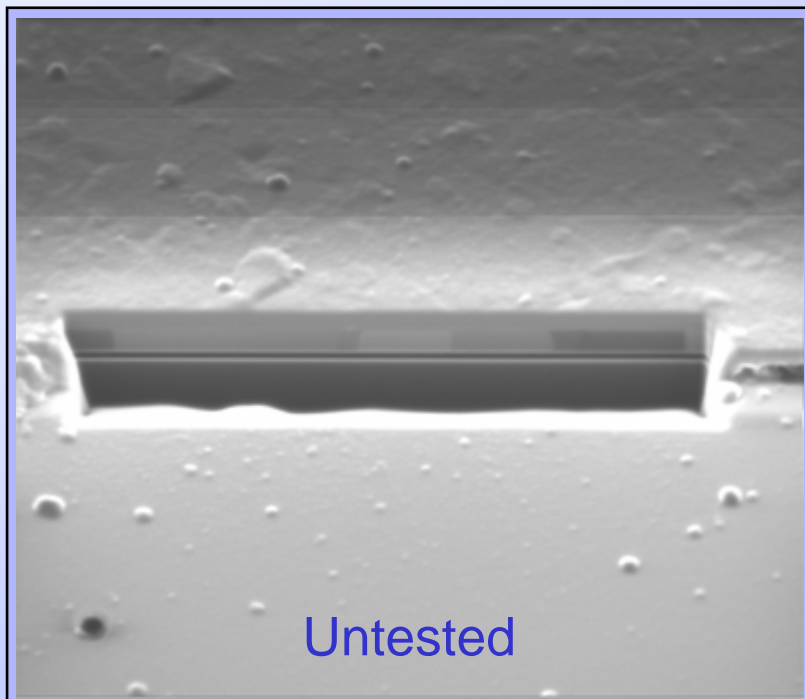Tested in AC at 11 MA/cm^2
Photoresist stripped in acetone

Conclusion: Soft overlayer does not change damage morphology.
Speculation: Cu/low-k systems could spell trouble…

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Effect of Hard Passivation

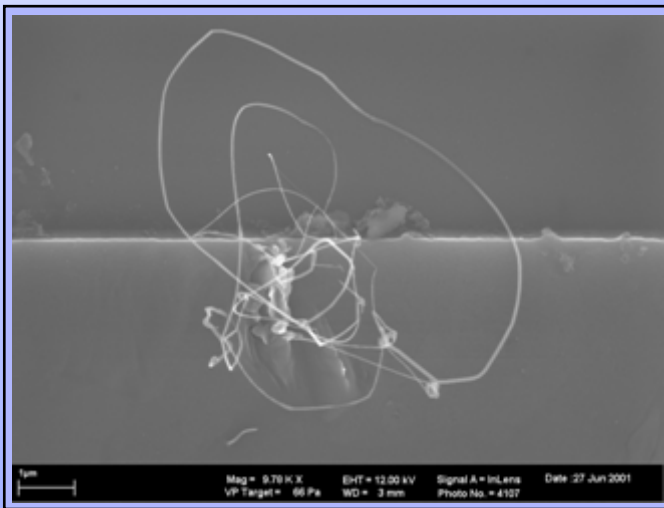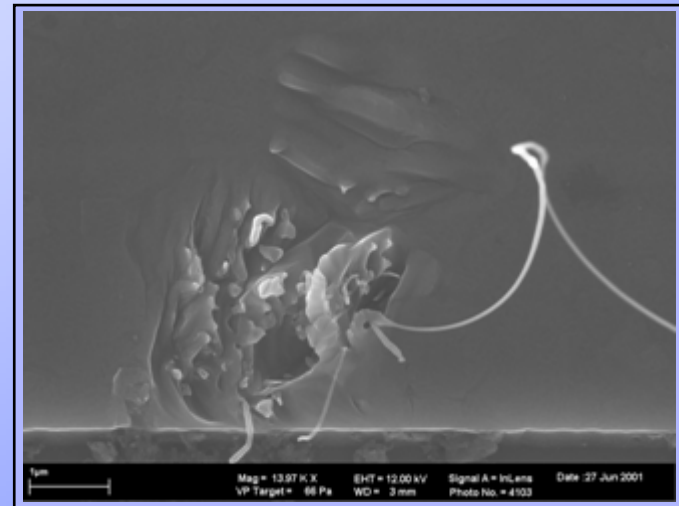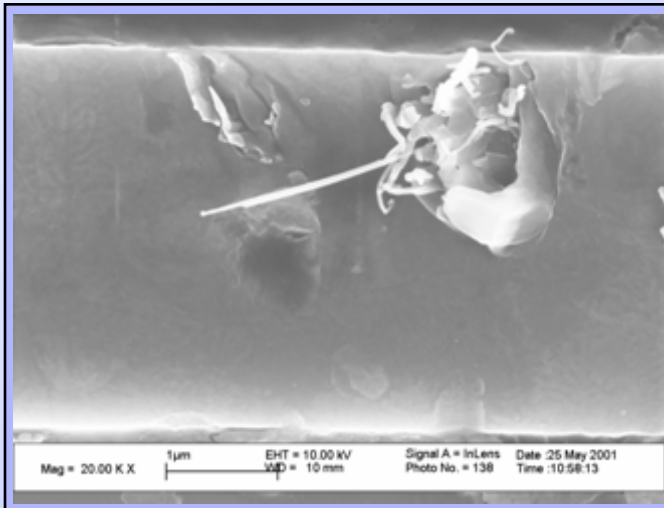Coated with 0.3 μm Si_3N_4;Tested in AC at 11 MA/cm^2

Untested

AC-Tested

1 μm

Conclusion: If hard overlayer doesn't adhere well, still get damage.
Cannot yet say if well-adherent hard passivation inhibits damage.

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Whiskers...

Perhaps diffusion does indeed play an important role, supplementing the fatigue process.

Concluding Remarks

- AC Damage Distinctly Different from DC Damage
- Site Selectivity
  - Local microstructure is important
- Fatigue Concepts Seem to Apply
  - Temperature cycles, causing $\Delta\varepsilon$
  - Need more lifetime statistics, but seems consistent with nanostructure fatigue
- Soft Overlayers do NOT Prevent Damage
  - Cu/low-k systems may be susceptible
- Separation of Temperature and Current Effects
  - Pure fatigue versus EM
- NIST/MPI Test Structure Underway

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